

# Burns and Military Clothing

AD McLean

## ABSTRACT

Burn injury is a ubiquitous threat in the military environment. The risks during combat are well recognised, but the handling of fuel, oil, munitions and other hot or flammable materials during peacetime deployment and training also imposes an inherent risk of accidental burn injury.

Over the last hundred years, the burn threat in combat has ranged from nuclear weapons to small shoulder-launched missiles. Materials such as napalm and white phosphorus plainly present a risk of burn, but the threat extends to encompass personnel in vehicles attacked by anti-armour weapons, large missiles, fuel-air explosives and detonations/conflagrations on weapons platforms such as ships. Large numbers of burn casualties were caused at Pearl Harbor, in Hiroshima and Nagasaki, Vietnam, during the Arab/Israeli Wars and in the Falkland Islands conflict.

The threat from burns is unlikely to diminish, indeed new developments in weapons seek to exploit the vulnerability of the serviceman and servicewoman to burns.

Clothing can be a barrier to some types of burn - both inherently in the properties of the material, but also by trapping air between clothing layers. Conversely, ignition of the clothing may exacerbate a burn. There is hearsay that burnt clothing products within a wound may complicate the clinical management, or that materials that melt (thermoplastic materials) should not be worn if there is a burn threat. This paper explores the incidence of burn injury, the mechanisms of heat transfer to bare skin and skin covered by materials, and the published evidence for the complication of wound management by materials.

Even light-weight combat clothing can offer significant protection to skin from short duration flash burns; the most vulnerable areas are the parts of the body not covered - face and hands. Multi-layered combat clothing can offer significant protection for short periods from engulfment by flames; lightweight tropical wear with few layers offers little protection. Under high heat loads in the

laboratory, combat clothing can ignite, but there is little evidence that clothing ignition is a common occurrence in military burn casualties.

Thermoplastic materials have many benefits in civil and military clothing. There is little objective evidence that they exacerbate burns, or complicate burn management. Their use in military clothing must be based on objective evidence, not hearsay.

*"The best way to treat a burn is not to have one." (Gaston 1965)*

## Introduction

Burns are a significant cause of morbidity and mortality in the military environment - in combat and peacetime - but the impact of clothing on burns is not addressed adequately in the medical literature. This article aims to condense published and unpublished material in this area from various medical and non-medical sources, discuss scientific and theoretical aspects of burn injury and the impact of clothing on the incidence, severity and management of burn injury.

## Military significance

Burns are an important cause of injury in modern conflict. The US Naval Hospital at Pearl Harbor treated 254 cases of burns on 7th December 1941 (Saxl 1942); the majority had superficial burns with some mixed partial and full thickness burns. Burns extended over exposed skin only, despite the common aetiology from high explosive munitions or flash fires from burning fuel and oil. Even white cotton T-shirts provided protection to the areas of skin covered from these flash burns.

In Vietnam, Hardaway demonstrated a burns incidence of 2.57% in the sample of 17,726 US military hospital admissions in 1966-7. The majority were accidental (54%) rather than inflicted in combat (Hardaway 1978). Arnold and Cutting documented the mortality in US military hospitals in Vietnam in 1969 and 3.1% of all deaths were due to burns (Arnold and Cutting 1978).

In the armoured battles between the Arabs and Israelis in 1973, 10.5% of all injured troops were burned. Measures to improve thermal protection were taken and this figure was reduced to 8% in the Lebanon War in 1982. During this latter conflict, nearly half of

Maj A D McLean BSc  
MB Ch B FRCS Ed  
RAMC

Biophysics Group,  
Biomedical Sciences,  
DERA Porton Down,  
Salisbury,  
SP4 0JQ

all burns casualties were tank crewman. The remainder were sustained by other combat troops or inflicted accidentally. The severity of burns was also reduced compared to 1973; half of the burn injuries in 1982 involved less than 10% total body surface area burn (TBSAB), (Shafir *et al* 1984) - Table 1.

Table 1. Total body surface area burned (TBSAB) in Israeli military personnel (from Shafir *et al* 1984).

TBSAB	1-9 %	10-19 %	20-39 %	40-60 %	>60 %
Lebanon War 1982	51	24	7	14	4
October War 1973	21	29	21		29

During the Falkland Islands conflict in 1982, 14% of all UK casualties were burned; 34% of RN casualties were burned (Chapman 1983). These burns were predominantly caused by bombs or guided missiles. Guided missiles are explosive but can behave as incendiary devices with combustion of any unburned fuel propellant, or cause a conflagration with combustion of the explosive charge if it fails to detonate.

Armoured vehicles and ships share the particular danger of shaped charge high-explosive penetration into a confined space, with potential for further explosion of fuel and explosives stored nearby. Other threats include conventional explosives, fuel-air explosives and other enhanced blast weapons, and accidental fires from stored fuels and munitions.

Burns are not confined to armed conflict - during the period 1980-1993, there were 785 fires reported onboard RN ships, with 382 documented injuries and 2 fatalities. Scalds were responsible for almost half of the burns and fire or explosions for one fifth (Skinner *et al* 1995; Rich 1997).

### Burn Pathology

The burn wound has concentric zones of decreasing tissue injury. A central zone of coagulated tissue exists, with denatured protein and destruction of tissue structures and cells. Surrounding this in three dimensions is a zone of stasis, with oedema and decreased tissue perfusion. Permanent tissue destruction can extend into this zone if perfusion is inadequate due to delayed resuscitation. The outermost zone is hyperaemic with evidence of an inflammatory reaction.

Burns are classified according to the degree of tissue injury. Minor injury can be described as erythema, with onset within 24 hours but resolving within 3-7 days without tissue loss. *Superficial partial thickness loss* has areas of blistering and will heal within 10-21 days if protected from infection. Further exposure will cause *deep dermal loss* with preservation of epidermal appendages; these burns are red or yellowy-white in colour and are occasionally described as having a "salt and pepper" appearance with visible flecks. These burns

are moist and will require more than 21 days for spontaneous healing, and may develop unsightly hypertrophic scarring. *Full thickness loss* is characterised by anaesthetic, leathery or charred skin which may have visible thrombosed vessels, is dry and all but the smallest areas will require surgery for prompt healing.

The mortality and morbidity of burns is related to various factors, the most important being TBSAB, the age of the casualty and the presence or absence of inhalation injury (Darling *et al* 1996; Thompson *et al* 1986; Germann *et al* 1997). The increased mortality associated with patients over 60 years of age is not relevant to the military casualty, but may be important in peacekeeping operations. Factors such as pre-morbid nutritional deficiency, concomitant neurological, pulmonary, cardiac, hepatic or renal impairment may become components in multiple trauma or multi-organ failure. Factors such as female gender, nicotine and alcohol excess are less important in the population below 60 years of age (Germann *et al* 1997).

### Military Burns

Burns in the military environment can be divided into four groups:

- combat related burns due directly to munitions;
- combat related burns from ignition of fuel, explosives, propellants and clothing;
- industrial-type accidental injuries due to working with vehicles, fuel, hot liquids and electrical equipment;
- off-duty accidental injuries.

In general, there is a higher incidence of burns within military vehicles, to both crew and passengers. The heat and flame threats to vehicle crew in combat are from four main sources:

- burning fuels and lubricants;
- burning ammunition or propellants carried in the vehicle;
- penetration of the vehicle by warheads, such as a shaped-charge munitions;
- the thermal pulse from a nuclear detonation.

Burns in the industrial (non-combat) environment are associated with an increased TBSAB (Ng *et al* 1991; Pegg *et al* 1986; Hull *et al* 1985), with flames from ignition of clothing causing the most severe injuries (Pegg *et al*). In the series reported by Ng *et al*, electrical burns accounted for 27.5% of all burns, of which 49% were flash burns. Flame burns caused 24.4% of all burns in this series, with 40% of these being due to explosion of flammable material, but 60% were due to clothing ignited by sparks or a source of intense heat or flame.

It is important to recognise the increased hazard of clothing contaminated with oil and

fuel spillage. The material is highly flammable and any areas of oil impregnation increase the thermal conductivity of the material, despite any flame retardant properties the material may inherently possess.

In one industrial accident, marked differences attributed to clothing were seen in injury severity after an explosion in an aerosol production plant. Those wearing synthetic clothing generally had worse injuries compared to colleagues in close proximity wearing natural fibres. The difference between burn severity was 5-15% TBSAB. As an example, one casualty wearing natural fibres received 60% TBSAB and survived; 5 casualties further from the blast epicentre who were wearing synthetic materials had greater TBSAB injuries, and two died (Hull *et al* 1985).

Military deployment will expose personnel to accidental injury unrelated to combat. This is associated with road traffic accidents, smoking and the use of unguarded flames for lighting, cooking and heating. The medical literature discusses clothing in relation to the extremes of age and casual clothing rather than related to the military situation (Crikelair *et al* 1976; Turner *et al* 1989; Laing 1991; Kalayi and Mohammad 1994).

### Energy Transfer

Thermal energy is transferred by conduction, convection and radiation. Clothing can ignite and increase the contribution of all 3 components to the burn - particularly conduction and convection.

#### Conduction

Conduction occurs at the skin surface from contact with any hot object or substance. The rate of transfer of heat is directly proportional to the temperature gradient and is determined by the conductivity of skin. This is Fourier's law and the principle also applies to the transfer of energy within skin and deeper tissues.

Metals tend to be good conductors; gases and liquids are poorly conductive and skin is a relative thermal insulator (Lawton 1997). As skin absorbs thermal energy, the tissue temperature does not rise proportionally. Some heat is carried away by increased blood flow from vasodilatation. More energy is required to produce a given burn if the energy is delivered at a low rate. This property of requiring more energy per unit temperature rise if delivered at lower intensity, is described as thermal inertia and is more important at lower temperatures (50°C, 323K). Because of this variability, skin can be described as an imperfect thermal energy absorber (Stoll and Greene 1959) and, at higher thermal energy doses, up to one third of burn damage is caused during the cooling phase of burn injury (Stoll and Chianta 1971).

#### Convection

Convection occurs when a hot liquid or gas flows in contact with any surface. The liquid or gas layer in contact assumes the temperature of the surface and, at a distance from the surface, the liquid or gas temperature is that of the bulk of the material. The boundary layer lies between the bulk temperature and the surface temperature, its thickness being determined by various factors such as temperature, density, viscosity, turbulence and velocity of the moving heat source. Energy transfer by convection also obeys Fourier's law and its calculation relies on experimentally derived values and constants; these differ for natural and forced convection. Convection also carries flames and burn products vertically upwards and explains the incidence of burn injury at the waist band and around the neck area in otherwise protected individuals (Elton 1996). A separate smock and trouser ensemble accounts for the incidence of these types of burns around the waistband, related to rising flames (Elton 1996), rather than exposure of the skin by rucking of the material (Shafir *et al* 1984). The speed of a burning object such as a human moving above 3 m/s, will cause flames to be carried behind the object, explaining the preponderance of burns to the back in fleeing individuals (Stoll and Chianta 1971).

#### Radiation

Radiant energy is emitted by any surface with a temperature above absolute zero; radiant energy will pass through a vacuum or gas. The wavelength of the radiant energy is directly proportional to the source temperature in Kelvin (K) and the magnitude of radiant energy is proportional to the fourth power of the temperature in Kelvin. On striking a surface, a proportion will be reflected, a proportion absorbed and the remainder transmitted into the surface. The proportions will depend on the incident wavelength and the properties of the incident surface. Radiant energy can pass through respirator lenses and cause ocular damage, it can also pass through windows or viewing slots with sufficient energy to ignite materials within otherwise closed spaces, such as buildings and vehicles.

Radiation from a fireball is also a factor for an individual in flight. Some anomalies occur, such as the incidence of facial burns to fire-fighters glancing back at a fire.

Skin allows some penetration before absorption but no radiant energy is transmitted deep into the tissues. The proportion reflected will depend on the surface colour and the electromagnetic frequency of incident radiation. White skin will reflect 42% of solar radiation (source temperature 6000 K, wavelength 0.5µm), but will only reflect 5% of longer wavelength radiation from a source temperature below

1300 K (Buettner in Lawton 1997).

Buettner calculated the depth of tissue penetration for solar radiation. White skin will absorb 58% of solar radiation. Forty five percent will penetrate 0.1mm; 40% will penetrate 0.2mm, 19% will penetrate 1.0mm, and 10% will penetrate 2.0mm.

For black skin, 90% of solar radiation is absorbed. Eighty percent will penetrate 0.1mm and 35% will penetrate 0.2mm. Buettner calculated that 40% of solar energy is absorbed in the basal epidermal layer (around 0.15 mm) for black skin and explains why black skin will burn more readily than white for high temperature radiation (adapted from Buettner, in Lawton 1997).

### Thermal Injury

The tissue temperatures achieved during a burn and the depth of penetration will determine the severity of tissue injury, and thus the burn depth. The depth of energy penetration depends on the amount of energy released, the duration of thermal load and the optical and thermal properties of skin. Skin is an imperfect thermal energy absorber - thermal conductivity and thermal inertia increase with increasing skin temperature, attributed in part to vasodilatation and blood flow.

#### *Experimental thermal injury*

Experimentally, thermal injuries have been reproduced by various methods and a time/temperature relationship has been demonstrated (Stoll and Greene 1959; Davies 1997). Hot liquid scalds are a common household injury with temperatures of between 65 and 100°C, whereas flames or contact with very hot surfaces are between 100 and 500°C (370 and 770K). Temperatures in industrial and military burns can be considerably higher. A fireball burning with a bright yellow flame will be at a temperature of 1370K, an orange flame at 1220K (Prugh 1994). Although experimental sources are conductive, convective or radiant, assessment of the skin temperature allows a degree of comparison in terms of the amount of thermal energy applied to cause pain or tissue damage.

The *total* thermal energy delivered is described in joules per unit area (thermal fluence or heat dose), however the *rate* of energy delivery may be more important and this is the thermal flux, with units of watts per unit area.

With exposure durations of 200 ms and temperatures of 1000 -3000K, Evans *et al* (in Davies 1997) showed the energy required to cause burns in terms of heat dose:

- 84-134 kJ/m<sup>2</sup> produced erythema;
- 134-160 kJ/m<sup>2</sup> produced erythema with areas of partial thickness loss;
- 164-197 kJ/m<sup>2</sup> produced deep dermal burns;

- greater than 202 kJ/m<sup>2</sup> produced full thickness loss.

Morton *et al* (1952), used a radiant source for 1 s exposures and reported:

- 126 kJ/m<sup>2</sup> produced erythema;
- 230 kJ/m<sup>2</sup> produced patchy deep dermal or full thickness loss;
- greater than 356 kJ/m<sup>2</sup> produced varying degrees of skin charring.

Prugh (1994) summarised the data from a total of 47 “notable fireball incidents” between 1943 and 1992 and there is broad agreement with these figures.

#### *Military thermal injury*

The detonation of a high explosive or a fuel-air explosive in the open will result in a fireball - the hot products of combustion. These products will also heat air. The fireball radiates heat for a few tenths of a second. The products and hot air will also flow over any objects near to the detonation, resulting in heat transfer by convection. Although the fireball has a predictable diameter (Prugh 1994), the heated air may flow further, thus increasing the incidence of convection heat burns beyond the fireball. With large explosive charges such as fuel-air explosive or explosives with a high energy output as heat (thermobaric explosives - see Dearden in this volume), burns from radiation and convection are one of the principal injury outcomes. If explosives are detonated in a room, the confinement of the products will increase the incidence of burns.

With penetration of armours, the radiant heat may show a number of peaks related to shaped charge jet formation, combustion of armour debris, fuel-flash and combustion of material within the vehicle. Energy release from a high explosive anti-tank round shows two distinct peaks, with a maximum to second peak time of 40 milliseconds (Gardner *et al* 1978). Although the flux is very high, the duration is relatively short.

Deflagration is the rapid burning of a substance, such as occurs with petrol. At extreme burn rates, this may be just short of a detonation. The casualty is exposed to considerable thermal energy as a combination of radiant and convective energy. Fuel-air explosives that fail to detonate may generate large amounts of heat by the deflagration of the fuel.

Conflagration describes the destruction caused by an extensive and intense fire. The term “flashover” is used by some to describe the envelopment in a ball of flame but, more strictly, is the point at which all of the combustible material has ignited in an enclosed space (House and Squire 1997 and 1998). Flashover and conflagration have dual convective and radiant components and the duration and intensity of thermal flux will determine the extent of thermal injury.

The combustion processes outlined above

involve very different thermal injury profiles and an attempt has been made to provide an appropriate standard to allow comparative assessment of thermal protection in these scenarios (Allied Combat Clothing Publication - 2, 1992).

- Burning fuels would provide a moderately high flux ( $150 \text{ kW/m}^2$ ) for several seconds. The time to evacuation if otherwise uninjured is estimated at 7-12 seconds; exposure to this degree of flux beyond this time period is generally considered fatal.
- Exploding ammunition or burning propellants are considered to provide a higher thermal flux ( $200 \text{ kW/m}^2$ ) and for purposes of testing, it is assumed that if the victim does not escape in less than 5 seconds, the environment is not survivable due to a combination of thermal injury, blast injury and inhalation of toxic combustion products.
- The thermal load from penetration of confined spaces by warheads will depend on the type of munitions, and the performance and composition of the armour. The thermal flux may be very high ( $500\text{-}560 \text{ kW/m}^2$ ) but for very short time periods - less than 0.3 seconds.

### Thermal Protection

Thermal protection is the provision of effective insulation to protect the skin and superficial tissues by the reduction in transfer of thermal energy. Clothing can be manufactured to provide very effective thermal protection but bulkiness, moisture vapour permeability and thermal insulation will determine the impact on military efficiency in various environments. The protection afforded by a clothing ensemble will be determined by the properties of each layer and their effective properties in combination.

Important factors are:

- colour and reflectivity;
- composition;
- coating or intrinsic fire retardant properties;
- thermal conductivity;
- flammability;
- air trapping within, or between, layers;
- moisture content;
- contamination with combustible materials such as oil.

The hands and face are prone to burn injury by their relative exposure. Injuries to these areas will significantly degrade military performance, but a balanced approach must be taken in providing protection. Inappropriate eye protection will impair visual acuity, and some approaches to hand protection will impair tactility, routine coarse or fine motor performance and military effectiveness. The incidence and severity of burns to Israeli tank crew casualties were reduced significantly simply by the provision of Nomex<sup>TM</sup> anti-flash hoods and gloves, and

4mm polycarbonate lenses in protective goggles (Shafir *et al* 1984).

Stoll and Chianta demonstrated the value of a 4 mm air gap, which increased thermal protection threefold (Stoll and Chianta 1971), in an otherwise identical clothing ensemble. Beyond 4mm, the degree of protection was reduced, by a combination of convection within the air gap and disintegration of the material. They also demonstrated that for flame burns, a darker material outer layer with an insulating inner layer was better protection than a highly reflective outer layer (they did not specify any inner insulating layer). The darker layer can emit absorbed radiant energy more effectively, before the passage of thermal energy through the insulating inner layers and more deeply to the skin, during the cooling phase.

### Materials in Clothing

Materials can be described as thermoplastic if they soften and/or melt before degrading or combusting. Thermal degradation without the oxidative change of combustion is termed pyrolysis. A synthetic material such as Nylon 6 will soften at  $50^\circ\text{C}$  and melt at  $215^\circ\text{C}$  and, although it will not combust until  $450^\circ\text{C}$ , it will shrink and reduce or eliminate the effect of any insulating layer of air held within the original volume of the fabric (Horrocks 1983). Thermoplastic materials may not propagate a flame and appear to self-extinguish, but by shrinking away from a flame, or by melting and dripping away, will expose the wearer to the direct heat of the source (Crikelair *et al* 1976).

It is assumed that thermal energy is absorbed as latent heat of fusion when the material melts. When melted onto the skin, this heat will then be delivered to the skin and superficial tissues in a continuing manner as it solidifies again, potentially increasing the thermal dose delivered and tissue damaged in heating and cooling phases. Although the physical processes will undoubtedly occur, there is little quantitative information in the literature to support the view that this is a notable contributor to the burn - the rate of heat release to the tissues in the solidifying process may be quite slow and capable of being dissipated by conduction and blood flow.

In a review of 585 burn patients by Darko *et al*, one third described ignition of clothing and, although this was immediate in 90%, the fabric only melted in 13.2% (Darko *et al* 1986).

Most clothing materials will ignite if the temperature is high enough and potentially deliver thermal energy from this process to the skin and underlying layers. The total energy liberated by combustion of material will not necessarily be transferred to the skin and the proportion of energy transferred will depend on the material, undergarment, air gaps and any pre-treatment. A broad figure of 15-50%

is quoted by Lees (1994).

Viscose rayon is formed from wood pulp and is a filamentous form of cellulose. Cotton, wool and viscose rayon, are not thermoplastic and will not shrink in response to heat. At 245°C for untreated wool and 350°C for cotton and viscose rayon, a carbonaceous “char” is formed, with volatile liquids and gases generated, before combustion at 600°C, 350°C and 420°C respectively (Horrocks 1983).

Synthetic material fibres are stronger than most natural fibres and clothing manufactured from them can be made lighter and warmer by incorporating air spaces. This characteristic enables wet synthetic clothing to dry more quickly but, when burning, is a more open structure and may burn rapidly and completely. Mixtures of synthetic and natural materials can behave detrimentally - the non-thermoplastic material may support the burning of thermoplastic material within its char and propagate the combustion. This is termed “scaffolding” and although demonstrated experimentally with clothing samples, appears to be unusual in combat burn simulations. The favourable qualities of lightness, warmth, permeability to moisture vapour, quick drying and durability, mean that these materials are ideal for combat personnel in adverse conditions.

Specialised fabrics such as Nomex™ or Kevlar™ are thermoplastic, but will not soften until 275°C and 340°C and they melt at 375°C and 560°C respectively. These materials will not burn until temperatures reach more than 500°C and 550°C respectively, but their action as sole protection against burns is limited by other factors such as thermal conductivity (Knox *et al* 1974, Horrocks 1983).

A fire retardant material such as Nomex™ with high thermal conductivity, will require an effective inner insulating layer to prevent conduction through the materials to the skin surface. Nomex™ as an outer layer with an equal mixture of wool and cotton as undergarment was found to be significantly better protection than Nomex™ as outer and inner layers against flame exposure over 1.75s duration. The extent of any air gap is not made clear, but a two layer Nomex™ system is also significantly better than a single layer of Nomex™ for any tested duration (Knox *et al* 1974).

The fire retardance of textiles can be enhanced by additives or coatings. The mechanisms of action can differ, but the aim is to prevent combustion or to increase the magnitude of the thermal energy required to cause combustion. These mechanisms may include the production of a barrier to oxygen, or stabilising intermediate pyrolysis products and forming a char, thus preventing the formation of flammable, volatile products (Horrocks 1983, Elmes 1999). Although a coating is generally easier to produce, factors

such as the robustness, handling and durability after laundering, are important. Modifying the materials during manufacture may affect the handling or production processes.

### Clothing and clinical effects

Using a porcine “living skin model”, Knox *et al* studied the effects of fibre and dye degradation products (FDP) on the healing of burn wounds (Knox *et al* 1979). They found that different materials gave off markedly different gases when the materials were burning, and some left residue on the skin. This residue depended on the composition of the clothing layering, but did not adversely affect wound healing. Wound healing was assessed for initiation of epithelialisation, contraction of open sites of biopsy wounds, time of open wound closure and the amount and type of scar tissue formation. The amounts of FDP visible in the wounds were diminished after 24 hours, and always absent after one week. The degradation products could be washed away with water, or removed with a dermatome prior to split skin grafting. No dye or fabric products penetrated the epidermis and no significant differences in wound healing were noted. The control areas without any fabric covering always healed more slowly. This was attributed to more severe burns without any thermal protection.

Galbraith (1998) discusses the recollections of military surgeons who served in the Falkland Islands war who dealt with both the early assessment and management of burns and the subsequent definitive treatment of the British forces’ burn casualties. They did not recollect that thermoplastic materials caused any difficulties in the management of burns, but there is no contemporaneous medical literature.

Brigadier BC McDermott (Retired Consultant Adviser in Burns and Plastic Surgery to the Defence Medical Services) has no recollection of clothing - thermoplastic or not - having any impact on the distribution, severity, management or healing of burns in this group of patients (personal communication, Oct 2000).

One concern is that the absorption of toxic products such as hydrocyanic acid and aniline was more likely through the breached epithelium and could reach systemic toxic levels. Knox *et al* calculated that the absorbed dose required for systemic toxicity would exceed that produced by the entire combustion of a flying suit and that this conflagration would be fatal (Knox *et al* 1979). The levels of toxic products from household or industrial fires will cause respiratory toxicity rather than systemic effects from absorption through the skin.

Products of clothing combustion such as nitrogen dioxide, hydrochloric acid, hydrocyanic acid, acrolein (propenal) and carbon monoxide, may be toxic if inhaled in

small quantities (Terrill *et al* 1978). Volatile products of pyrolysis such as aldehydes, alcohols and alkanes can ignite if temperatures are high enough. Natural and synthetic materials will burn at high enough temperatures in air to produce smoke, which can be incapacitating or lethal. Smoke is a suspension of carbon particles in air, causing respiratory distress at doses of 1 g/m<sup>3</sup> (Treitman *et al* 1980). This figure will be reduced if other toxic combustion products are present.

The morbidity and mortality associated with airway involvement can be broadly considered in relation to time from injury. Immediate injury or death by asphyxiation from overwhelming products of combustion may occur without airway burn injury. Upper airway burn injury may cause early respiratory compromise by oedema and airway occlusion, and although treatment is by ventilatory control, this is only possible with awareness, clinical suspicion and the anaesthetic facilities to allow early and elective endotracheal intubation.

Parenchymal lung damage sufficient to compromise respiratory function may not present immediately, but over the following 12-48 hours, and cause complications over the medium and long term. This may be evolution of the local burn injury or part of the systemic response to burn injury.

### Clothing Testing

The effect of clothing on heat transfer and burn incidence and severity can be assessed on animals, isolated clothing samples, mannequins, or computer modelling (Knox *et al* 1974; Knox *et al* 1978; Behnke 1984; Bamford and Boydell 1995; Staples 1996; House and Squire 1997; Elton 1999; NATO ACCP-2 1992).

Armoured Fighting Vehicle (AFV) personnel and passengers are a group of combat soldiers at increased risk of fire from specific anti-armour munitions and the materials in the vehicle (propellants, ammunition, fuel etc.). Attempts have been made to standardise clothing testing throughout NATO and the likely military threat has been broadly grouped under three situations - NATO ACCP-2 (1992), outlined above.

The ACCP-2 protocol with thermal loads are for "worst case scenarios". These protocols have been used for standard combat clothing testing and have been criticised as "swamping" any small advantages between various clothing ensembles for soldiers in the open (Elton 1996). In operational practice, a small difference in protection may actually have a notable benefit. As the distance from a thermal source increases, the area of ground involved increases by the square of the distance and the thermal dose diminishes exponentially. At extended ranges, a larger number of personnel may be subjected to a

much smaller burn threat.

Under the severe ACCP-2 conditions, it has been estimated that bare skin would receive a partial thickness burn within 0.11s for a weapon detonation flash, within 0.18s for exploding ammunition and within 0.12s for a flashover event (MOD reports). Under these conditions, the standard combat smock is sufficient protection for preventing partial thickness burns over any covered skin, but this does not include a component of clothing ignition.

The performance of current Tropical and Arctic ensembles has been compared with standard Combat Soldier 1995 (CS 95) clothing, including the presence of woollen jumper or Norwegian shirt - and therefore air gaps (Elton 1996). With longer durations of 50kW/m<sup>2</sup> intensity, the results for CS 95 clothing were predictable - considering the protection afforded by the multiple layers - compared with the lightweight polyester/cotton mix of Tropical combat clothing. In this test the times to partial thickness burns were:

Tropical Combats	1s
Temperate Combats Dry	6s
Temperate Combats Wet	15s
Arctic Combat Clothing	20s

(From Elton 1996).

The component from clothing ignition has been assessed using a vertical mannequin for trials of flame engulfment provided by an array of gas burners. In this experiment, if ignition occurred, the ensemble was left to self-extinguish, but the ensemble was extinguished if this did not occur promptly. A lightweight ensemble with cotton "Long Johns" was engulfed in flames for one second without clothing ignition or any burns to covered skin. Exposure of the same ensemble for 2s caused combustion and, although there was convective spread up the mannequin, partial thickness burn was estimated to occur only after 22s.

Using an ensemble comprising combat smock, Norwegian shirt, cotton "Long Johns" and lightweight trousers in similar severe conditions but for 4s flame engulfment, clothing ignition occurred and did not self-extinguish, with an estimated time of 7s before partial thickness burning occurred. This would suggest that under these situations, the composition of the clothing is less important than extraction from the flame source and extinguishing of the ignited clothing.

It would seem obvious that a fire retardant material would give better protection, however in comparative studies for AFV crewman's coveralls, the fire retardant material with the longest time before partial thickness burn was not the most protective with regard to TBSAB. A fire retardant material may increase the duration of survivable flame engulfment by decreasing the TBSAB, but airway protection may be just as important for

survival.

The effectiveness of the thermal protection can be improved by increasing the insulating layers, but is inversely proportional to the physiological load to the wearer with increased perspiration, physical encumbrance and impairment in performance.

## Key points

### *General considerations*

The military environment exposes personnel to an increased risk of burn injury in peacetime and combat; non-combat burns have predominated in recent years. Military technological advances include weapons that present a high risk of burns. The logistic chain and medical capability is limited and combat related burns can present in large numbers. Burn injury can cause immediate, medium term and long term disability.

### *Flash burns*

Flash burns cause very superficial damage which may be incapacitating if the eyes, mouth or hands are affected, but they heal quickly with minimal medical intervention. Tropical combat clothing provides good protection for any covered skin against flash burns as long as the material does not ignite. The standard combat clothing is considerably thicker than lightweight tropical clothing and provides very good protection against flash burns and the ability to withstand longer exposure to a more intense radiant energy source because of insulating layers and decreased heat transfer to the skin.

### *Flame engulfment*

Combat related burns due to engulfment by flames or any hot material are survivable for a few seconds in standard multi-layered combat clothing, but not with tropical combat wear. Tropical combat clothing offers little protection against prolonged exposure to flames because of the single layer composition, the risk of combustion and subsequent direct exposure to a thermal source. The standard Combat Soldier 1995 smock is effectively double layered down to the waist, and is usually worn with at least one more layer beneath. The trousers are unlined; lining would decrease wearer comfort and drying of the material, but it would increase protection from burns. Standard issue "Long Johns" are cotton, but Lycra™ and other synthetic materials offer improved comfort and practical advantages in austere conditions.

Any system can be overwhelmed and extraction from fire is as important as clothing protection. Combat Soldier 1995 clothing is not resistant to ignition and although the high thermal fluences necessary to cause combustion are likely to endanger life by their magnitude with the risk of large burn and inhalation injury, fire resistant clothing may

improve survival.

Ignition of combat clothing is likely to worsen burn injury *per se* and can be plainly demonstrated in the laboratory, but there is little evidence to suggest that clothing ignition actually occurs in practice in the military burn casualty.

There is no evidence that combustion products from thermoplastic and combat clothing have contributed to burn severity or have required an alteration to conventional clinical management.

### *Military considerations*

The incidence of accidental and peacetime injury is considerable and day to day clothing needs to provide adequate protection against this burn aetiology. Of the 785 fires reported aboard Royal Navy ships during the period 1988-1994, two thirds were extinguished by personnel in normal working dress (Rich *et al* 1997).

Different trades will require varying degrees of thermal protection and some may require different clothing for a given situation - for example, Royal Marines or infantry soldiers when deployed onboard ships rather than during transportation by land or air. It must be recognised that although crew clothing may be designed to reduce the burn threat, passengers in transit in the many forms of military transport are also exposed to the same threat. At present, passengers are not supplied with such clothing.

Developments in weaponry, particularly those in blast weapons discussed by Dearden and Galbraith in this journal, will increase the incidence of flash burns to unprotected areas.

Equipment limitations or shortcomings tend to be multi-factorial, but the ensemble will need to be viewed as a whole. Improvements in reducing limb or torso burns without hand, eye or airway protection may be futile and, in the standard infantry role, facial protection is not currently widely available.

The danger of thermal conduction and clothing ignition in relation to fuel and oil stains is considerable and facilities should exist for replacement or laundry. Similar "special to trade" dangers related to the immediate working environment should be brought to the attention of all personnel.

### *Education*

Thermal protection clothing must be practical and appropriate to the environment, but the education of soldiers is important; soldiers will wear matériel of choice. The principle of trapped air should be emphasised, whether this is between layers or within insulating materials, but soldiers will wear clothing in which they feel comfortable.

There are misconceptions about the role of thermoplastic materials in burns injury. There is little objective evidence that they worsen burns. As a single layer over skin, they may disintegrate and thus cease to function as a

barrier. Worn beneath a flame resistant outer layer, their insulating properties would mitigate injuries. Synthetic materials have many valuable properties with regard to military clothing and decisions on their use should be on the basis of objective, scientific evaluation of their comfort and burn protection performance - the latter defined using instrumented models and defined thermal challenges, not hearsay.

### The Future

The Defence Logistic Organisation (Defence Clothing and Textiles) is responsible for military clothing. The DLO and other organisations within MoD are undertaking research into burn models, alternative clothing materials and coatings for materials subject to heat. There are still difficult challenges in burn protection, foremost of these in combat related burns is prevention of burns to the face, a very difficult area to protect. One expedient approach is to use lightweight materials as physical barriers (similar to the hoods worn by racing drivers). With careful design, the physiological penalty can be minimised by, for example, allowing physiological heat loss through the crown of the head, and use of materials that “wick” perspiration to the outer surface of the material.

Ocular protection will require the use of transparent materials but this will inevitably reduce the field of view, promote misting and may not be fully compatible with current weapon sights. These challenges are currently being reviewed within DLO and DERA.

There are other more novel approaches. DERA is developing a barrier cream for the face that can reflect some of the radiation from a detonation fireball and scavenge heat transferred into the barrier cream by radiation or convection. The cream is designed to protect the face from flash burns, not flame engulfment.

### Conclusion

Burns are a very effective method of wounding with long-term military incapacitation; weapon designers will seek to exploit this vulnerability. Non-combat related burn threats are always present. The effects of burns on the individual and the impact on military and civilian medical facilities are notable. There are misconceptions about the contribution some forms of clothing and materials make to the severity and complications in the medical management of burns. There is a difficult balance of comfort, durability and burn protection in the design of military clothing. “*The best way to treat a burn is not to have one*” states the obvious; solutions may not be quite so obvious. This paper has sought to outline some of the aspects of the burn threat and some of the limitations of protection against burns in the military environment.

Some of the difficult aspects of the burn threat are extremely challenging; research is underway within MoD and DERA to enhance protection from the ubiquitous threat of burns.

### Acknowledgements

A DERA report by written by Col K Galbraith L/RAMC discusses burns and clothing in detail and I am pleased to acknowledge the insight offered by this report. The report details are presented below.

### References

- Allied Combat Clothing Publication - 2, Edition 1. Protection from Flame and Heat Resistance Provided by AFV Crewman Clothing. NATO Document Group on Standardization of Matériel and Engineering Practices, Sub-Group B on Materials, Mechanical Parts and General Engineering Working Group 5 on Combat Clothing and Personal Equipment. June 1992; AC/301-N/1.
- Arnold K and Cutting RT. Causes of Death in United States Military Personnel Hospitalized in Vietnam. *Military Medicine* 1978; **143** (3): 161-164.
- Bamford GJ and Boydell W. ICARUS: A Code for Evaluating Burn Injuries. *Fire Technology* 1995; **31** (4): 307-335.
- Behnke WP. Predicting Flash Fire Protection of Clothing from Laboratory Tests Using Second-degree Burn to Rate Performance. *Fire and Materials* 1984; **8** (2): 57-63.
- Elton S. UK Research into Protection from Flame and Intense Heat for Military Personnel. *Fire and Materials* 1996; **20**: 293-295.
- Elton SF. Modelling of Burn Beneath Clothing Layers (ICARUS) Final Report. Science and Technology Division, Defence Clothing and Textiles Agency Research Report 99/02, April 1999.
- Evans EI, Brooks JW, Schmidt FH *et al.* Flash burn studies on human volunteers. *Surgery* 1955; **37**: 280-297.
- Galbraith KA and Cooper GJ. Medical aspects of the burn threat to military personnel. Defence Evaluation and Research Agency Report 98/053, March 1999.
- Gardner L, Simpson GN and Cox AFJ. Flash Protection programme for image intensifiers - Warminster trials. Royal Signals & Radar Establishment Memorandum 3430, 1978. Quoted in House JR and Squire J. Anti-Flash Protection for Royal Naval Personnel, *vide infra*.
- Gaston SR. Reply to lecture presentation by GF Crikelair, “Flame Retardant Clothing.” American Association for the Surgery of Trauma 1965, Philadelphia. *Published in J Trauma* 1966; **6** (3): 427.
- Germann G, Barthold U, Lefering R, *et al.* The impact of risk factors and pre-existing conditions on the mortality of burns patients and the precision of predictive admission-scoring systems. *Burns* 1997; **23** (3): 195-203.
- Hardaway RM III. Viet Nam Wound Analysis. *J Trauma* 1978; **18** (9): 635-643.
- Horrocks AR. An Introduction to the Burning Behaviour of Cellulosic Fibres. *J Society of Dyers and Colourists* 1983; **99**: 191-197.
- House JR and Squire J. Anti-Flash Protection for Royal Naval Personnel - The risk of burn injury to the head and hands from explosions, fuel fires or backdraughts and the effectiveness of the in service hood and gloves. Institute of Naval Medicine Report 97038, August 1997.
- House JR and Squire J. The protection from burns afforded by the prototype Naval action clothing system. Institute of Naval Medicine Report 98057, October 1998.
- Hull D, Grindlinger GA, Hirsch EF *et al.* The Clinical Consequences of an Industrial Aerosol Plant Explosion. *J Trauma* 1985; **25** (4): 303-308.

- Kalayi GD and Muhammad I. Clothing burns in Zaria. *Burns* 1994; **20** (4): 356-359.
- Knox FS III, McCahan GR and Wachtel TL. Use of the Pig as a Bioassay Substrate for Evaluation of Thermal Protective Clothing and Physical Sensor Calibration. *Aerospace Medicine* 1974; **45** (8): 933-938.
- Knox FS III, Wachtel TL and Knapp SC. How to measure the burn-preventive capability of non-flammable textiles: a comparison of the USAARL porcine bioassay technique with mathematical models. *Burns* 1978; **5** (1): 19-29.
- Knox FS III, Wachtel TL, McCahan GR and Knapp SC. Effects of Fiber and Dye Degradation Products (FDP) on Burn Wound Healing. *Aviation, Space, and Environmental Medicine* 1979; **50** (10): 1007-1015.
- Laing RM. Prevention of burn injuries to children involving nightwear. *New Zealand Medical Journal* 1991; **104**: 363-365.
- Lawton. Heat Transfer to Tissues, in *Scientific Foundations of Trauma*. Eds Cooper GJ *et al.* Butterworth-Heinemann, Oxford 1997.
- Lees FP. The Assessment of Major Hazards: A model for fatal Injury from Burns. *Transactions of The Institute of Chemical Engineers* 1994; **72** (B): 127-134.
- Morton JH, Kingsley HD and Pearse HE. Studies on flash burns: Threshold burns. *Surgery, Gynecology and Obstetrics* 1952; **94**: 317-322.
- Ng D, Anastakis D, Douglas LG and Peters WJ. Work-related burns: a 6-year retrospective study. *Burns* 1991; **17** (2): 151-154.
- McDermott BC. Retired Consultant Adviser in Burns and Plastic Surgery to the Army. Personal communication, October 2000.
- Pegg SP, Miller PM, Sticklen EJ and Storie WJ. Epidemiology of industrial burns in Brisbane. *Burns* 1986; **12** (7): 484-490.
- Prugh RW. Quantitative Evaluation of Fireball Hazards. *Process Safety Progress* 1994; **13** (2): 83-91.
- Rich K, House J and Skinner A. The influence of clothing on injuries from fire in the Royal Navy. *Journal of Defence Science* 1997; **2** (2): 200-204.
- Saxl NT. Burns en masse. *US Naval Medical Bulletin* 1942; **40**: 570-576.
- Shafir R, Nili E and Kedem R. Burn injury and prevention in the Lebanon War 1982. *Israeli Journal of Medical Science* 1984; **20**: 311-313
- Skinner AJ, House J and Rich KJN. A review of fire, accident and burn injury data to establish whether in-service clothing is implicated as a causative or exacerbating factor in accidental injury. Institute of Naval Medicine Report Number 95025; May 1995.
- Staples R. Development of a Thermal Manikin to Test the Protection Offered by Clothing Assemblies from Flame and Intense Heat. Defence Clothing and Textiles Agency, Science and Technology Division Report 96/10, December 1996.
- Stoll AM and Greene LC. Relationship between pain and tissue damage due to thermal radiation. *J Appl Physiol* 1959; **14** (3): 373-382.
- Stoll AM and Chianta MA. Heat Transfer Through Fabrics as Related to Thermal Injury. *Transactions of the New York Academy of Sciences* 1971; **2** (33): 649-670.
- Terrill JB, Montgomery RR and Reinhardt CF. *Toxic Gases from Fires*. *Science* 1978; **200**: 1343-1347.
- Thompson PB, Herndon DN, Traber DL, *et al.* Effect on Mortality of Inhalational Injury. *J Trauma* 1986; **26** (2): 163-165.
- Treitman RD, Burgess WA and Gold A. Air contaminants encountered by firefighters. *American Industrial Hygiene Association Journal* 1980; **41**: 796-802.
- Turner DG, Leman CJ and Jordan MH. Cooking-Related Burn Injuries in the Elderly: Preventing the "Granny Gown" Burn. *Journal of Burn Care and Rehabilitation* 1989; **10**: 356-359.